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Intracluster Planetary Nebulae

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Abstract. I review the progress in research on intracluster planetary nebulae over the last five years. Hundreds more intracluster planetary nebulae have been detected in the nearby Virgo and Fornax galaxy clusters, searches of several galaxy groups have been made, and intracluster planetary candidates have been detected in the distant Coma cluster. The first theoretical studies of intracluster planetaries have also been completed, studying their utility as tracers of the intracluster light as a whole, and also as individual objects.

From the results to date, it appears that intracluster planetaries are common in galaxy clusters (10-20% of the total amount of starlight), but thus far, none have been detected in galaxy groups, a result which currently is not well understood. Limited spectroscopic follow-up of intracluster planetaries in Virgo indicate that they have a complex velocity structure, in agreement with numerical models of intracluster light. Hydrodynamic simulations of individual intracluster planetaries predict that their morphology is significantly altered by their intracluster environment, but their emission-line properties appear to be unaffected.

Keywords. planetary nebulae: general, galaxies: interactions, galaxies: clusters

1. Introduction

Intracluster starlight, the diffuse starlight which permeates many galaxy clusters, is potentially of great interest to studies of galaxy and galaxy cluster evolution. Since it is currently believed that the bulk of the intracluster stars were originally formed within galaxies and then were tidally removed from them, they are an important way to study the mechanisms of tidal stripping and interactions that are common within galaxy clusters (Dressler 1984). Modern numerical simulations of galaxy clusters show that the intracluster light is ubiquitous in galaxy clusters, has a complex spatial and kinematic structure, and can be used to gain information on the dynamical evolution of galaxies and galaxy clusters (Napolitano et al. 2003; Willman et al. 2004; Murante et al. 2004; Sommer-Larsen et al. 2005; Stanghellini et al. 2006; Rudick et al. 2006).

However, the obstacles in observing intracluster light in detail are substantial. Due to its low surface brightness (at the brightest, less than 1% of the night sky background in the V band), it is extremely difficult to image directly. There have been significant detections of intracluster light in galaxy clusters at low redshifts ($z < 0.3$) (Feldmeier et al. 2004a; Gonzalez et al. 2004; Mihos et al. 2005; Zibetti et al. 2005; Krick et al. 2006), but nearly all of these observations require specialized observing techniques that are extremely time-consuming to carry out. In addition, although intracluster imaging observations are crucial for obtaining a global view of the phenomenon, they can only give the spatial distribution of intracluster light, and possibly a color, meaning that detailed comparisons with the theoretical models will be difficult. Finally, despite heroic efforts, direct imaging cannot yet probe the lowest surface brightness features, which have surface brightnesses of $\mu_V = 32$ mag/sq. arcsecond.

An alternate way to study intracluster light is to detect luminous individual intracluster stars in nearby galaxy clusters, and gain more detailed information on the distribution, metallicity and velocities of intracluster stars than is possible from surface brightness measurements. This approach has also been quite successful: intracluster red giant stars (Ferguson, Tanvir, & von Hippel 1998; Durrell et al. 2002), intracluster H II regions (Lee et al. 2000; Gerhard et al. 2002; Ryan-Weber et al. 2004) and intracluster novae and supernovae (Gal-Yam et al. 2003; Neil, Shara, & Oegerle 2005) have all been detected in galaxy clusters.

Here, we focus on another luminous tracer of the intracluster light: intracluster planetary nebulae (hereafter, IPN). IPN have a number of unique advantages over other luminous tracers of the intracluster starlight. Because IPN are emission-line objects, they can be detected efficiently in [O III] λ 5007 surveys from the ground. Therefore, using wide-field imagers common on 4-meter class telescopes, samples of hundreds of candidates can be found in a single telescope run. With spectroscopic follow-up using 6-meter and larger telescopes, the radial velocities of IPN can be determined, offering the ability to study the dynamics of intracluster starlight.

2. History of IPN research and Current Status

The study of IPN is now over a decade old. During a radial velocity survey of planetary nebulae (PN) candidates in the Virgo elliptical galaxy M 86, Arnaboldi et al. (1996) found that 16 of the 19 detected PN velocities were consistent with the galaxy's mean velocity (v_{radial} = -227 km s^{-1}). The other three planetaries had mean radial velocities of $\sim$ 1600 km s^{-1}, more consistent with the Virgo cluster's mean velocity. Arnaboldi et al. (1996) argued convincingly that these objects were intracluster planetary nebulae, and it is here that the term first enters the literature. Almost simultaneously, the first search for IPN candidates in the Fornax cluster was published (Theuns & Warren 1997), and more detections of IPN candidates in Virgo quickly followed (Méndez et al. 1997; Ciardullo et al. 1998; Feldmeier, Ciardullo, & Jacoby 1998).

However, a surprise was in the works. Spectroscopic follow-up of the IPN candidates revealed that some were not IPN, but instead background emission-line objects with extremely high equivalent width (Freeman et al. 2000; Kudritzki et al. 2000). This was unexpected, because previous deep emission-line surveys had found very few such objects (Pritchet 1994), though many have now been detected at fainter magnitudes (Rhoads et al. 2004, and references therein). The most likely source of the contamination was found to be Lyman-α galaxies at redshifts 3.12–3.14, where the Lyman-α λ 1215 line has been redshifted into the [O III] λ 5007 filters used in IPN searches. However other types of contaminating objects may also exist (Stern et al. 2000; Norman et al. 2002).

Although these contaminants caused some consternation at first, a number of lines of evidence quickly showed that the majority of IPN candidates are in fact, actual IPN. Observations of blank control fields with identical search procedures as the IPN surveys (Ciardullo et al. 2002; Castro-Rodríguez et al. 2003) have found that the contamination fraction is significant, but was less than the observed IPN surface density. The surface densities found correspond to a contamination rate of $\approx$ 20% in the Virgo cluster and $\approx$ 50% in Fornax (Fornax is more distant than Virgo, so its luminosity function is fainter, and therefore further down the contaminating sources luminosity function). There are still significant uncertainties in the background density due to large-scale structure, and to the small numbers of contaminating objects found thus far. However, deeper and broader control fields are forthcoming (Gawiser et al. 2006). Spectroscopic follow-up of IPN candidates (Freeman et al 2000; Ciardullo et al. 2002; Arnaboldi et al. 2003, 2004),

Figure 1. Images of portions of the Virgo cluster (left) and the Fornax cluster(right). The regions surveyed for IPN are shown as the boxes in each image. There are over 400 IPN candidates detected in Virgo, and over 100 detected in Fornax at the current time.

clearly show large numbers of IPN candidates have the expected [O III] λ 5007 and 4959 emission lines, with a contamination rate similar to the blank field surveys.

Currently, with the widespread use of mosaic CCD detectors, and automated detection methods derived from DAOPHOT and SExtractor, over a hundred IPN candidates can be found in a single telescope run (Okamura et al 2002; Arnaboldi et al. 2003; Feldmeier et al. 2003, 2004b; Aguerri et al. 2005). IPN candidates are readily identified as stellar sources that appear in a deep [O III] λ 5007 image, but completely disappear in an image through a filter that does not contain the [O III] line. Currently, over 400 IPN candidates have been detected in the Virgo cluster, and over 100 IPN candidates have been found in the Fornax cluster. Figure 1 summarizes the status of the different imaging surveys. However, only a small portion of these ($\approx$ 50) have any spectroscopic follow-up at all, and many of those spectra have low signal-to-noise. However, despite all of the effort, to date, only a few percent of the total angular area of Virgo and Fornax have been surveyed. Literally thousands of IPN wait to be discovered by 4-meter class telescopes.

3. Obtaining the amount of intracluster light from IPN

In principle, determining the amount of intracluster luminosity from the observed numbers of IPN is straightforward. Theories of simple stellar populations (Renzini & Buzzoni 1986) have shown that the bolometric luminosity-specific stellar evolutionary flux of non-star-forming stellar populations should be $\sim 2 \times 10^{-11}$ stars-yr^{-1}-$L_{\odot}^{-1}$, (nearly) independent of population age or initial mass function. If the lifetime of the planetary nebula stage is $\sim 25,000$ yr, and if the empirical planetary nebula luminosity function (PNLF) is valid to $\sim$ 8 mag below the PNLF cutoff, then every stellar system should have $\alpha \sim 50 \times 10^{-8}$ PN-$L_{\odot}^{-1}$. According to the empirical PNLF, approximately one out of ten of these PNe will be within 2.5 mag of M^*. Thus, under the above assumptions, most stellar populations should have $\alpha_{2.5} \sim 50 \times 10^{-9}$ PN-$L_{\odot}^{-1}$. The observed number of IPN, coupled with the PNLF, can therefore be used to deduce the total luminosity of the underlying stellar population.

In practice, there are a number of systematic effects that must be accounted for before we can transform the numbers of IPN to a stellar luminosity (Feldmeier et al. 2004b; Aguerri et al. 2005), which we briefly summarize here. First, although stellar evolution theory originally predicted a constant $\alpha_{2.5}$ value for all non star-forming populations, observations (Ciardullo 1995; Ciardullo et al. 2005) and more sophisticated theoretical analysis (Buzzoni, Arnaboldi, & Corradi 2006) present a more complicated picture. Since the amount of intracluster starlight derived is inversely proportional to the $\alpha_{2.5}$ parameter, a large error in the amount of intracluster light can result if this is not accounted for. By comparing the numbers of IPN in a field surrounding a *HST* WFPC2 field, with RGB and AGB star counts, (Durrell et al. 2002) found a value of $\alpha_{2.5} = 23^{+10}_{-12} \times 10^{-9}$ PN-$L_{\odot}^{-1}$ for Virgo's intracluster population. Second, the IPN candidates of Virgo (and perhaps Fornax) may have a significant line-of-sight depth. Since the conversion between number of PN and luminosity depends on the shape of the luminosity function, this depth can change the amount of intracluster light found from the data. Models (Feldmeier, Ciardullo & Jacoby 1998) indicate that the difference between simple models of the intracluster star distribution, changes the derived intracluster star luminosity by up to a factor of three. Thus far, all IPN researchers have adopted a single distance model in order to be conservative, but this effect is the least studied at this point.

After applying the corrections, the intracluster stellar fractions for Virgo vary between 5 and 20% (Feldmeier et al. 2004b; Aguerri et al 2005), with the errors being dominated by the systematic effects. The IRG measurements (Ferguson, Tanvir & von Hippel 1998; Durrell et al 2002) find somewhat less intracluster light (10–15%), but the various results also agree within the errors.

4. What are the kinematics of the intracluster PN?

Since most IPN candidates that are detected photometrically can be followed up spectroscopically, IPN are an ideal, and perhaps only, way for studying the kinematics of the intracluster light. I will only briefly summarize this work here (see proceedings by Arnaboldi, Gerhard, this volume).

The state of the art in IPN kinematics is the work by Arnaboldi et al. (2004). Using a sample of 40 IPN over three fields in the Virgo cluster, Arnaboldi et al. (2004) showed that the radial velocity structure of Virgo's IPN varies from field to field, and is often asymmetric, as was predicted by the numerical models of intracluster starlight. This analysis used less than 10% of the known IPN candidates in Virgo: more spectroscopic follow-up is crucial for more detailed understanding. Curiously, at least three IPN of the Arnaboldi et al. (2004) have extreme velocities ($\Delta v \approx 1000$ km/s). A possible explanation of these objects is given by Holley-Bockelmann et al. (2005) who proposes that some hypervelocity intracluster stars may be ejected by supermassive black hole binaries.

5. What is the effect of the intracluster environment on the IPN?

IPN are located in a fundamentally different environment than PN in our own Galaxy or in other galaxies. They have enormous spatial velocities (1000 - 2000 km s^{-1}) and are embedded within the hot (T = 10^6 - 10^7 K) gaseous intracluster medium. as they move within the confines of a galaxy cluster. What effect, if any, do these hostile conditions have on the structure and the emission properties of the nebula?

At the the preceding IAU symposium, Feldmeier (2001) timidly suggested that the IPN might become aspherical, and possibly fragment, due to Rayleigh-Taylor instabilities. Recent theoretical work by Villaver & Stanghellini (2005; see also Villaver, this volume) has added immensely to our understanding of the internal structure of IPN. Using a hydrodynamic simulation of a 1 $M_\odot$ main sequence star progenitor, and physical conditions similar to a IPN within the Virgo cluster, Villaver & Stanghellini (2005) have found that the IPN becomes very aspherical in appearance compared to normal planetaries, with a long ($\approx$ 130 pc) gas stream that trails behind the IPN's direction of motion. However, Villaver & Stanghellini (2005) also find that the recombination emission appears to be unaffected in these objects, implying that the [O III] λ 5007 emission is unaffected as well. An interesting open question is whether any signs of the strong shocks seen in the simulations could be observed in a deep spectrum of the IPN.

6. IPN in more distant clusters

An exciting recent development is the detection of IPN candidates in the Coma cluster of galaxies, an extremely rich cluster at $\approx$ 100 Mpc, over a factor of six more distant than all previous IPN searches (Gerhard et al. 2004; see also Gerhard, Arnaboldi, this volume) These candidates were found using a technique of filling the entire focal plane of the 8-m Subaru telescope with a slit mask through the appropriate [O III] λ 5007 filter, and looking for narrow-line emission sources. Deep broad-band imaging has implied that the Coma Cluster may have a very high intracluster star fraction, up to 50% (Bernstein et al. 2005), so it is quite plausible that a few IPN could be detected, despite the relatively small area surveyed. The most exciting aspect of this observation is that it opens up a way to observe PN at much greater distances than previously thought possible, and makes it possible to place IPN density limits in more distant galaxy clusters. Additional observations using this method are now underway (Gerhard, private communication)

7. IPN searches in Galaxy Groups

In contrast, searches for IPN in galaxy groups have been less fruitful. Searches have been made of the M 81 galaxy group (Feldmeier et al. 2001; Feldmeier et al. 2006, in prep.), the Leo I galaxy group (Castro-Rodriguez et al. 2003), and the Hickson compact group HCG 44 (Castro-Rodriquez et al. 2005). In all three of these searches, no genuine IPN candidates have yet been found. Some emission-line sources have been detected, but their properties are consistent with background objects. The non-detections place a strong limit on intra-group starlight in these groups, over the regions searched, to limits of a few percent.

When compared with other measurements of intracluster star fractions through modern deep imaging (Feldmeier et al. 2004; Gonzalez et al. 2004; Zibetti et al. 2005; Krick et al. 2006), or through the detection of intracluster supernovae (Gal-Yam et al. 2003), an interesting pattern emerges, plotted in Figure 2. For galaxy clusters, the data is consistent with an approximate mean fraction of 15–20%. When we move to the group environment, the fraction abruptly drops, with no sign of any smooth decline. This feature, which we have dubbed the "intracluster cliff," is currently unexplained.

However, a theoretical paper by Sommer-Larsen (2006) has claimed that the intra-group fractions are quite high, between 12 and 45% How can this discrepancy be explained? Villaver & Stanghellini (2005) suggest that the higher density of the intragroup environment might cause a larger amount of gaseous stripping, and therefore the intra-group PN might be undetectable. Sommer-Larsen (2006) claims that the intra-group PN would be widely scattered, and the surveys to date do not cover a broad enough spatial range to detect the few objects that would be expected. Clearly, more observational studies are needed, over larger spatial scales of nearby galaxy groups to strengthen these results. An IPN survey of the intermediate Ursa Major galaxy cluster has also begun to address these questions.

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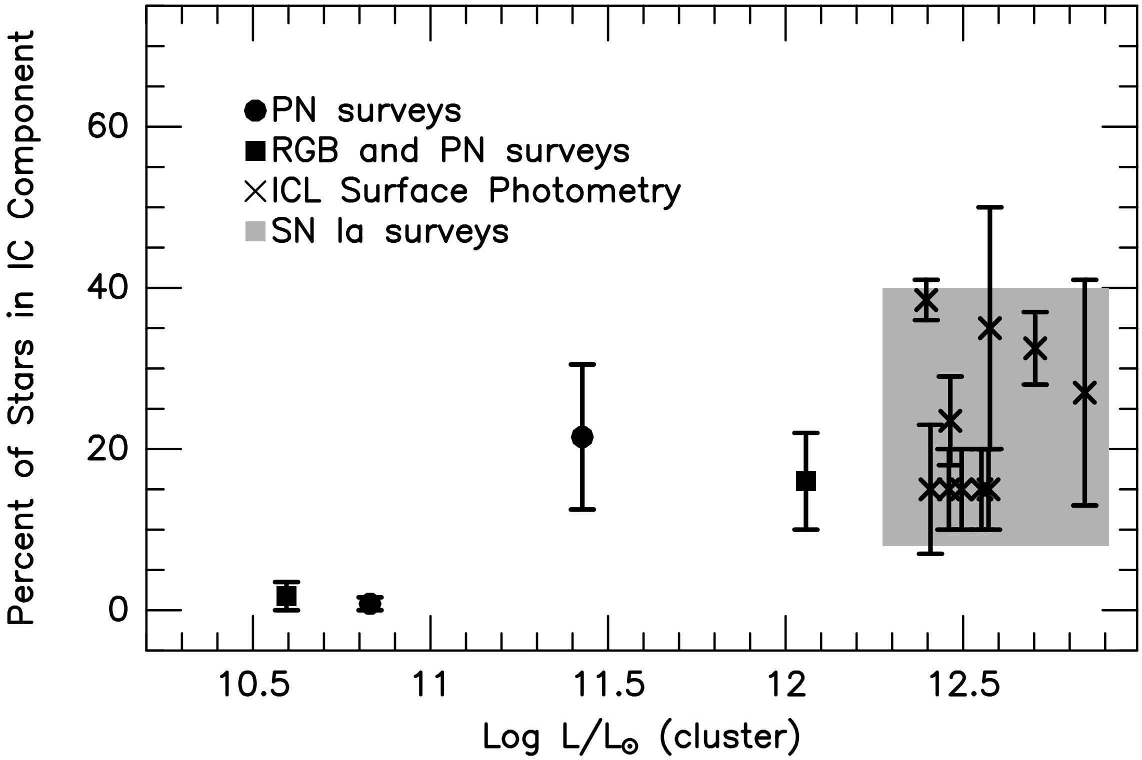

Figure 2. The fraction of intracluster starlight detected as a function of the cluster's total B-band luminosity. The data are consistent with a intracluster fraction of $\sim 20\%$ for massive systems, and then a drop to effectively zero for the two lowest mass groups. This "intracluster cliff" implies that something in the cluster environment promotes intracluster star production, but more data is needed to confirm these results.

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